Looking for Werner at RHIC

Feng Yuan

Lawrence Berkeley National Laboratory

RBRC, Brookhaven National Laboratory

easy

- News
- Publicatior
  talks
- Proposals

Brookhaven National Laboratory
Nuclear and Particle Physics
Program Advisory Committee
January 2010

e-mail	Name, Affiliation	Term Expires
dhbeck@uiuc.edu	Douglas Beck*, Illinois	7/31/12
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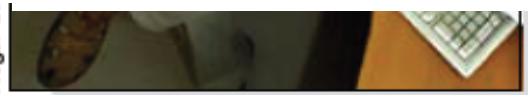
cggroup@comp.tamu.edu	Carl Gagliardi, Texas A&M	12/31/12
hemmick@skipper.physics.sunysb.edu	Thomas Hemmick, Stony Brook	7/31/10
makins@uiuc.edu	Naomi Makins, Illinois	11/30/10
bmck@caltech.edu	Bob McKeown, Caltech	12/31/12
krishna@mit.edu	Krishna Rajagopal, MIT	12/31/12
savage@phys.washington.edu	Martin Savage, Washington	11/30/10
werner.vogelsang@uni-tuebingen.de	Werner Vogelsang, Tuebingen	12/31/12
urs.wiedemann@cern.ch	Urs Wiedemann, CERN	11/30/10
xzb@bnl.gov	Zhangbu Xu, BNL	11/30/10



particles that has not been adequately answered, despite decades of study.

Looking Forward (rapidity) at RHIC

Feng Yuan

Lawrence Berkeley National Laboratory

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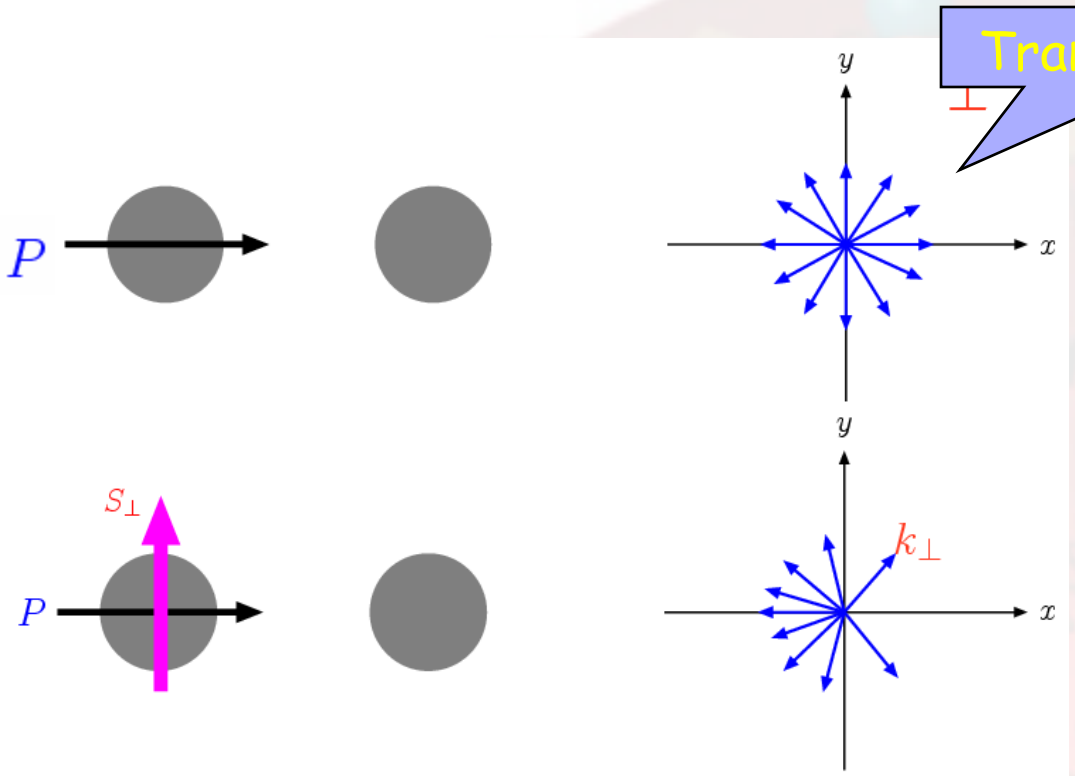
Great opportunities at forward direction of RHIC

- Transverse spin phenomena
- Saturation physics in dA collisions
- Many others…

Single spin asymmetry at forward

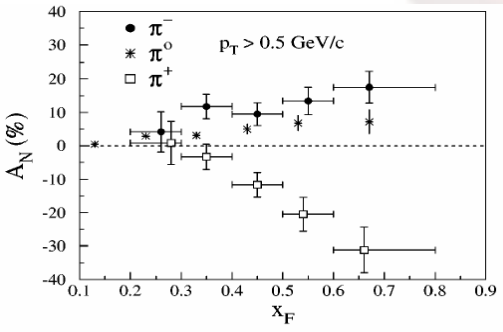


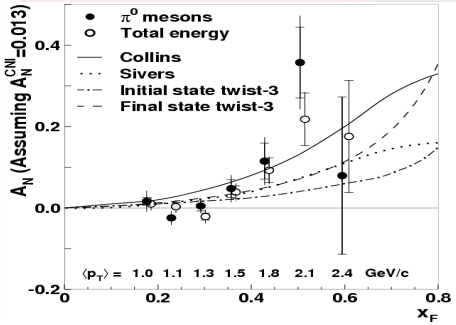
Final state particle is Azimuthal symmetric

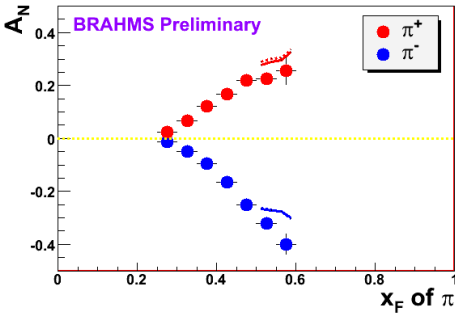
$$d\sigma \propto \vec{S}_\perp \cdot (\vec{P} \times \vec{K}_\perp)$$

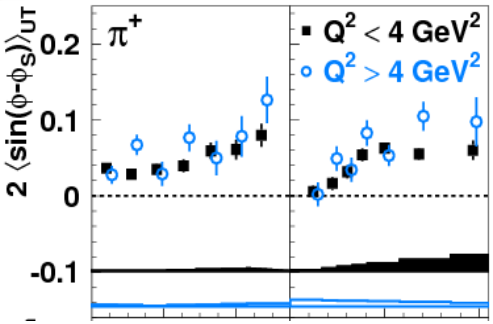
Single Transverse Spin Asymmetry (SSA)

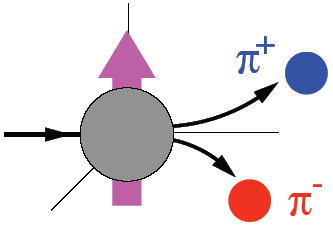
$$A_N = \frac{L-R}{L+R}$$





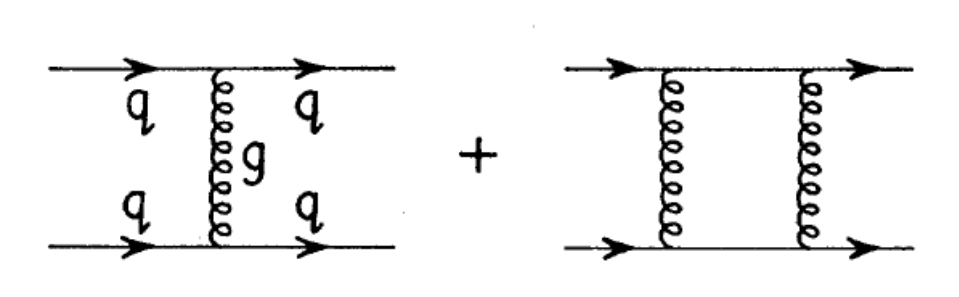




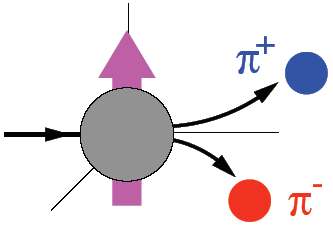


Naïve parton model fails

- If the underlying scattering mechanism is hard, the naïve parton model generates a very small SSA: (G. Kane et al, 1978),



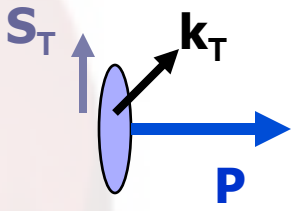
  - It is in general suppressed by $\alpha_S m_q/Q$
- We have to go beyond this naïve picture



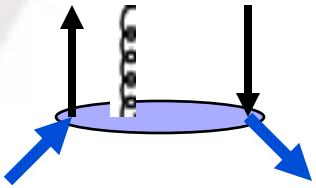
Two mechanisms in QCD

- Spin-dependent transverse momentum dependent (TMD) function
  - Sivers 90
  - Colllins 93
  - Brodsky-Hwang-Schmidt, 02

Sivers function ~ $S_T \cdot (PXk_T)$



- Twist-3 quark-gluon correlations (coll.)
  - Efremov-Teryaev, 82, 84
  - Qiu-Sterman, 91,98



PHYSICAL REVIEW D **74,** 114013 (2006)

Single transverse-spin asymmetry in high transverse momentum pion production in *pp* collisions

Chris Kouvaris,[1,*] Jian-Wei Qiu,[2,3,†] Werner Vogelsang, and Feng Yuan[4,§]

[1]*The Niels Bohr Institute, Blegdamsvej 17, DK-2100 Copenhagen 0, Denmark*
[2]*Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, USA*
[3]*Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA*
[4]*RIKEN BNL Research Center, Building 510A, Brookhaven National Laboratory, Upton, New York 11973, USA*

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We study the single-spin (left-right) asymmetry in single-inclusive pion production in hadronic scattering. This asymmetry is power-suppressed in the transverse momentum of the produced pion and can be analyzed in terms of twist-three parton correlation functions in the proton. We present new calculations of the corresponding partonic hard-scattering functions that include the so-called "non-derivative" contributions not previously considered in the literature. We find a remarkably simple structure of the results. We also present a brief phenomenological study of the spin asymmetry, taking into account data from fixed-target scattering and also the latest information available from Relativistic Heavy Ion Collider (RHIC). We make additional predictions that may be tested experimentally at RHIC.

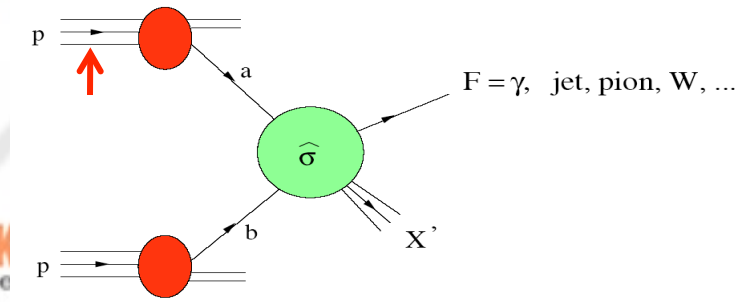
$$\Delta\sigma_{A+B\to hX}(\ell_\perp, \vec{s}_T) = \sum_{abc} \phi^{(3)}_{a/A}(x_1, x_2, \vec{s}_T) \otimes \phi_{b/B}(x') \otimes H_{ab\to c}(\ell_\perp, \vec{s}_T) \otimes D_{c\to h}(z)$$
$$+ \sum_{abc} \delta q_{a/A}(x, \vec{s}_T) \otimes \phi^{(3)}_{b/B}(x'_1, x'_2) \otimes H'_{ab\to c}(\ell_\perp, \vec{s}_T) \otimes D_{c\to h}(z)$$
$$+ \sum_{abc} \delta q_{a/A}(x, \vec{s}_T) \otimes \phi_{b/B}(x') \otimes H''_{ab\to c}(\ell_\perp, \vec{s}_T) \otimes D^{(3)}_{c\to h}(z_1, z_2)$$

Qiu-Sterman

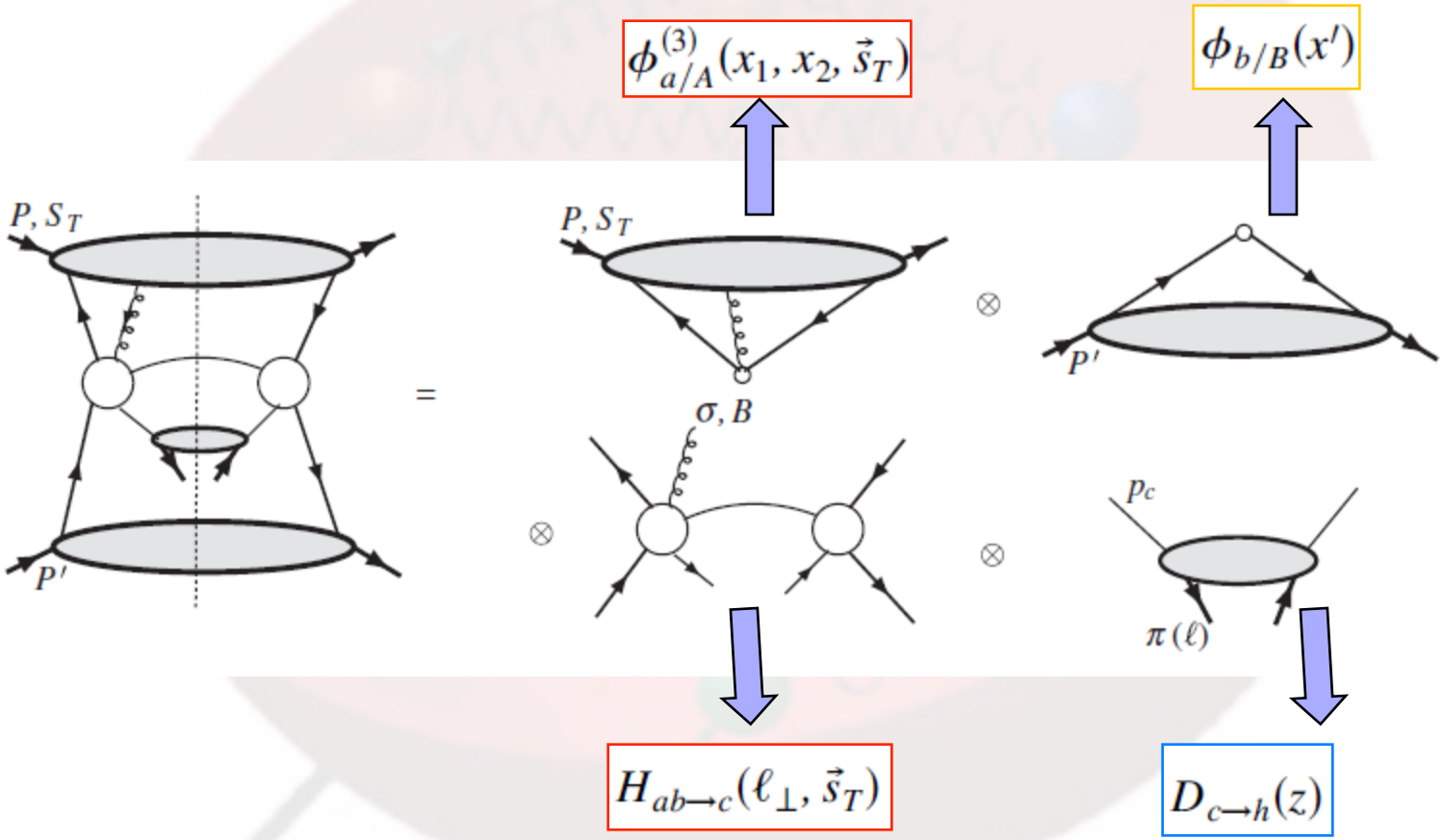
Qiu-Sterman;KQVY 06,10

Kanazawa-Koike 00

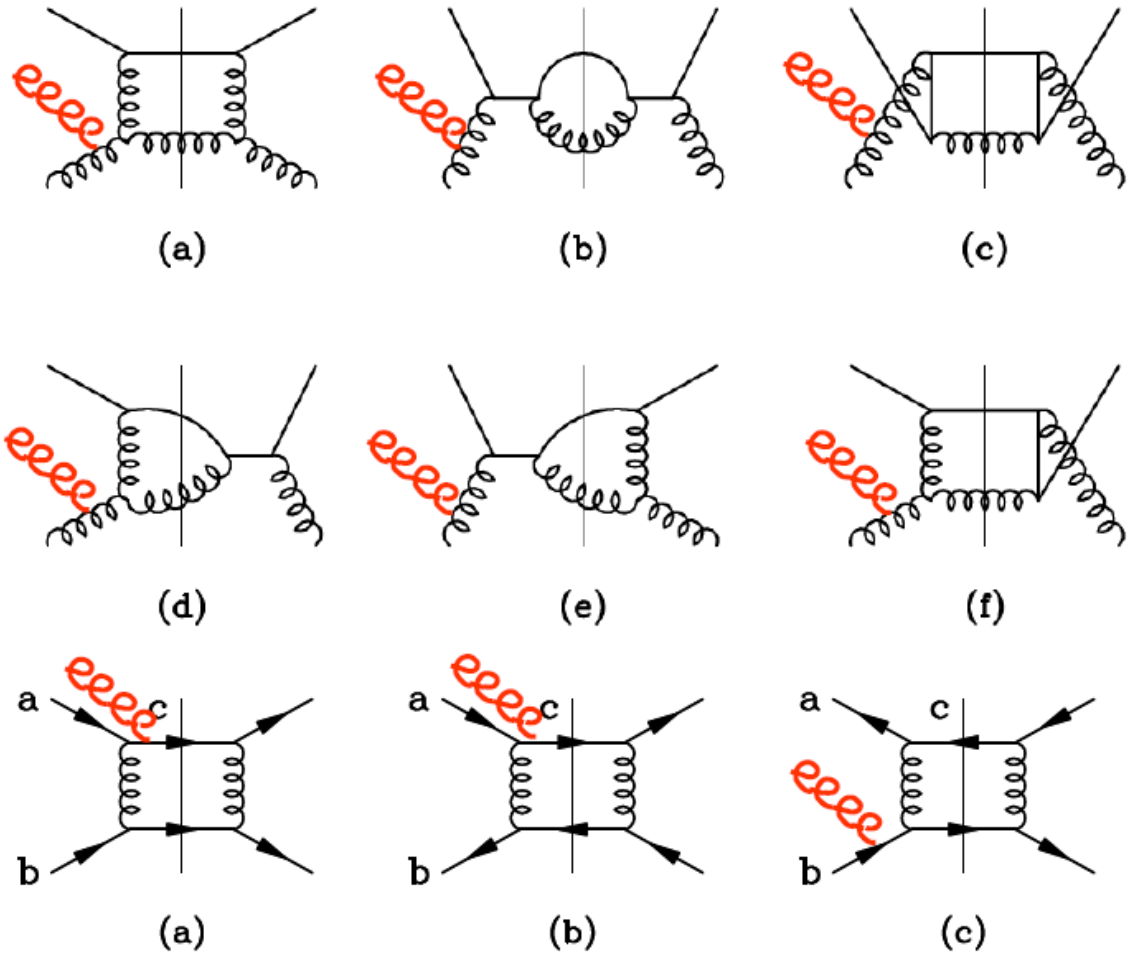
Kang-Yuan-Zhou 10



Collinear factorization



Twist-three diagrams



Courtesy of Werner

Remarkable simple results

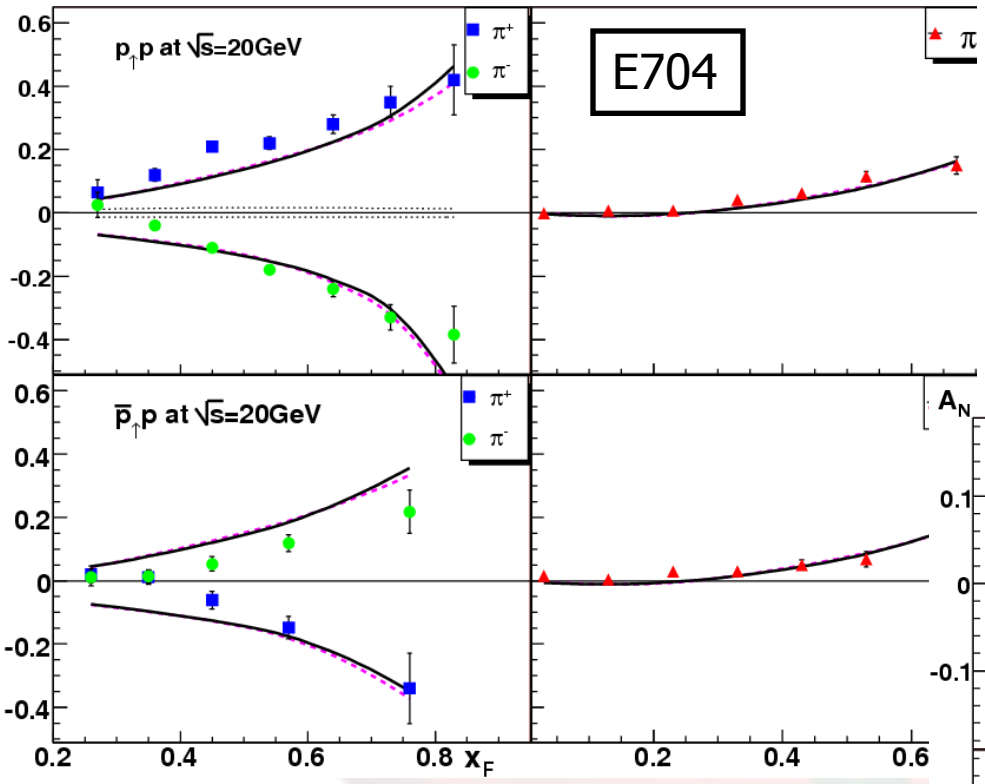
- single inclusive hadron production in pp collision, including the derivative and non-derivative terms

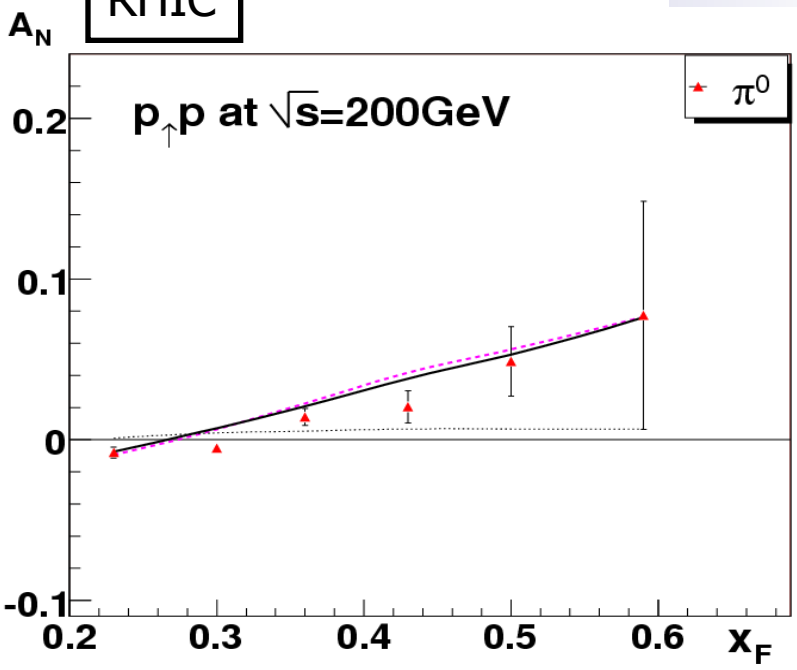
$$E_\ell \frac{d^3\Delta\sigma(\vec{s}_T)}{d^3\ell} = \frac{\alpha_s^2}{S} \sum_{a,b,c} \int_{z_{\min}}^1 \frac{dz}{z^2} D_{c\to h}(z) \int_{x'_{\min}}^1 \frac{dx'}{x'} \frac{1}{x'S + T/z} \phi_{b/B}(x')$$
$$\times \sqrt{4\pi\alpha_s} \left(\frac{\epsilon^{\ell s_T n\bar{n}}}{z\hat{u}}\right) \frac{1}{x} \left[T_{a,F}(x,x) - x\left(\frac{d}{dx} T_{a,F}(x,x)\right)\right] H_{ab\to c}(\hat{s},\hat{t},\hat{u})$$

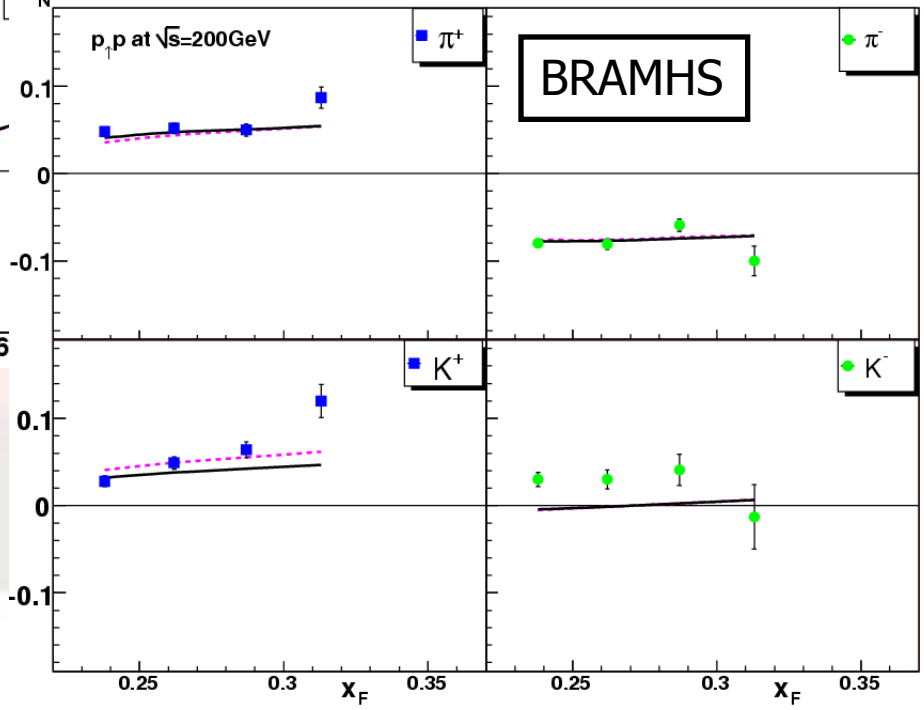
Qiu, Sterman, 91, 98
Kouvaris,Qiu,Vogelsang,Yuan, 06

Twist-3 Fit to data

$$p_{\uparrow}p \to \pi + X$$



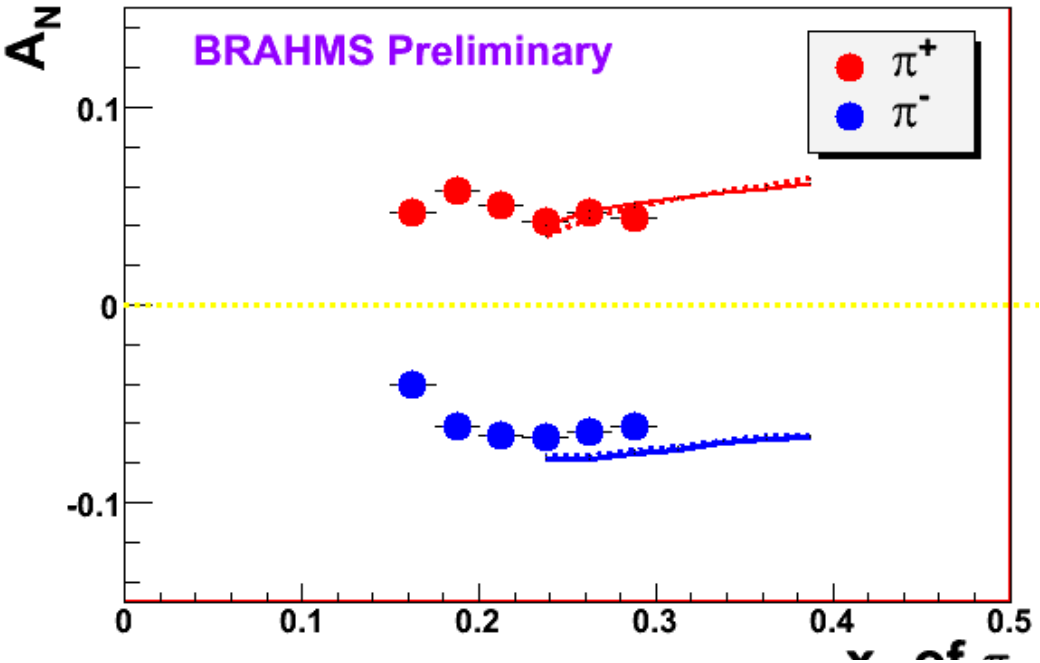


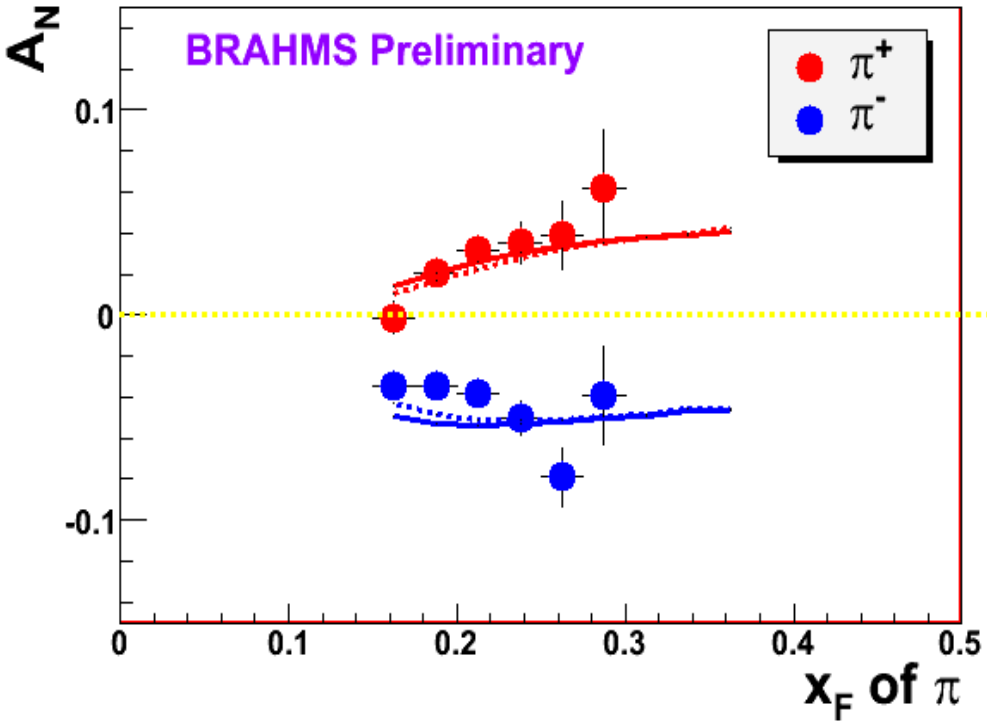


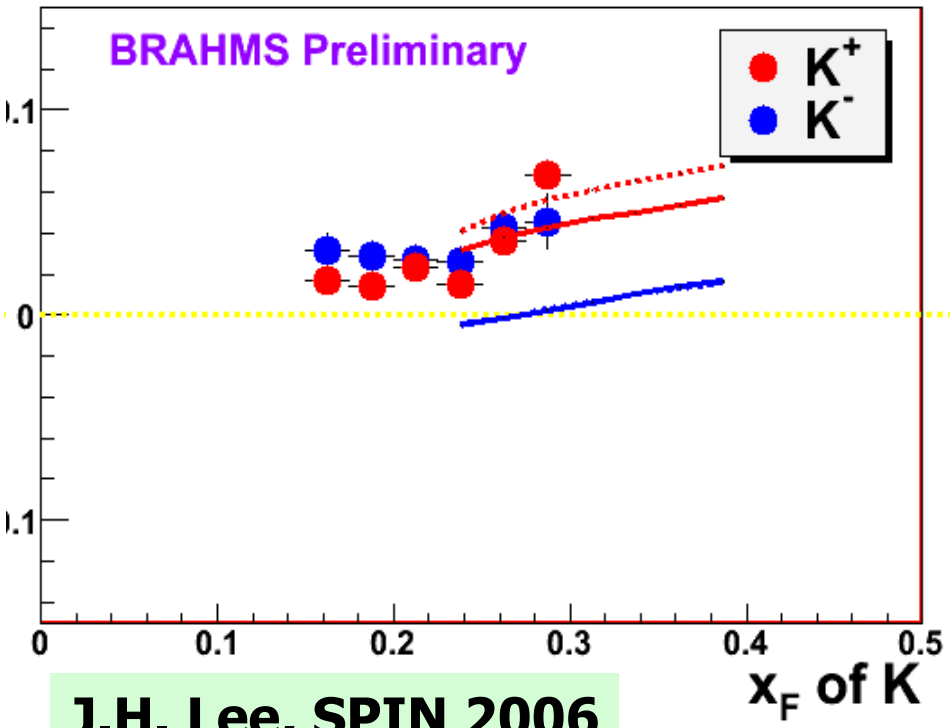
$$T_F^a(x) = N_a x^{\alpha_a}(1-x)^{\beta_a} f_a(x)$$

Kouvaris,Qiu,Vogelsang,Yuan, 06

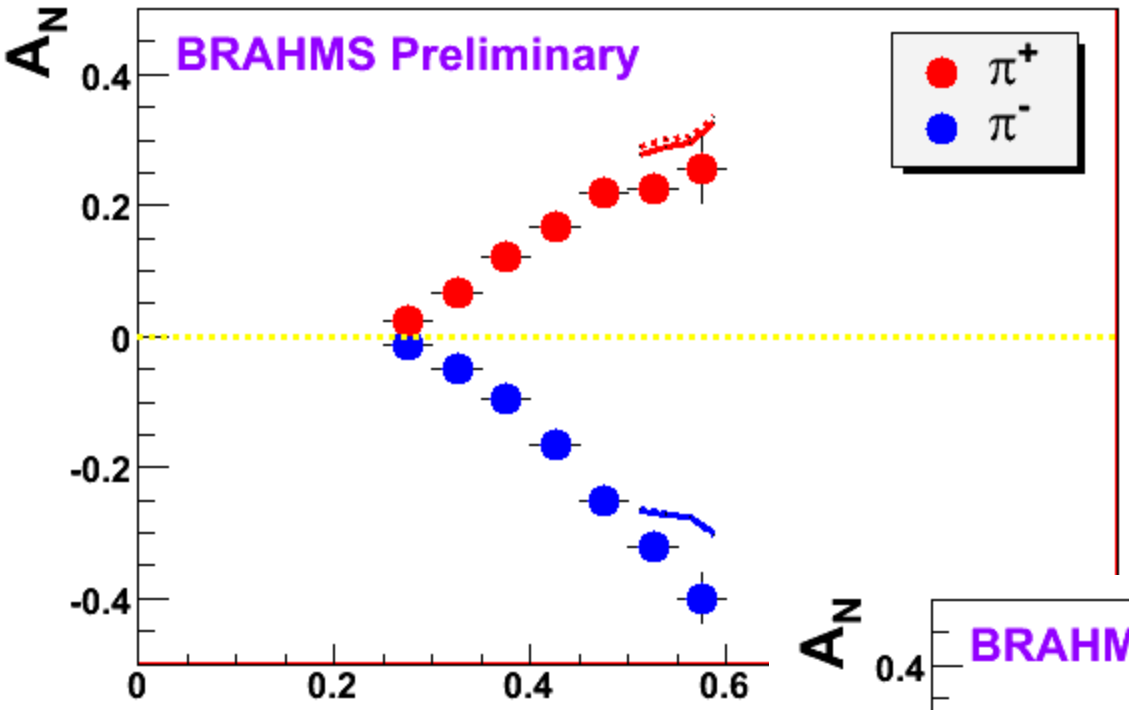
Compare to 2006 data from RHIC



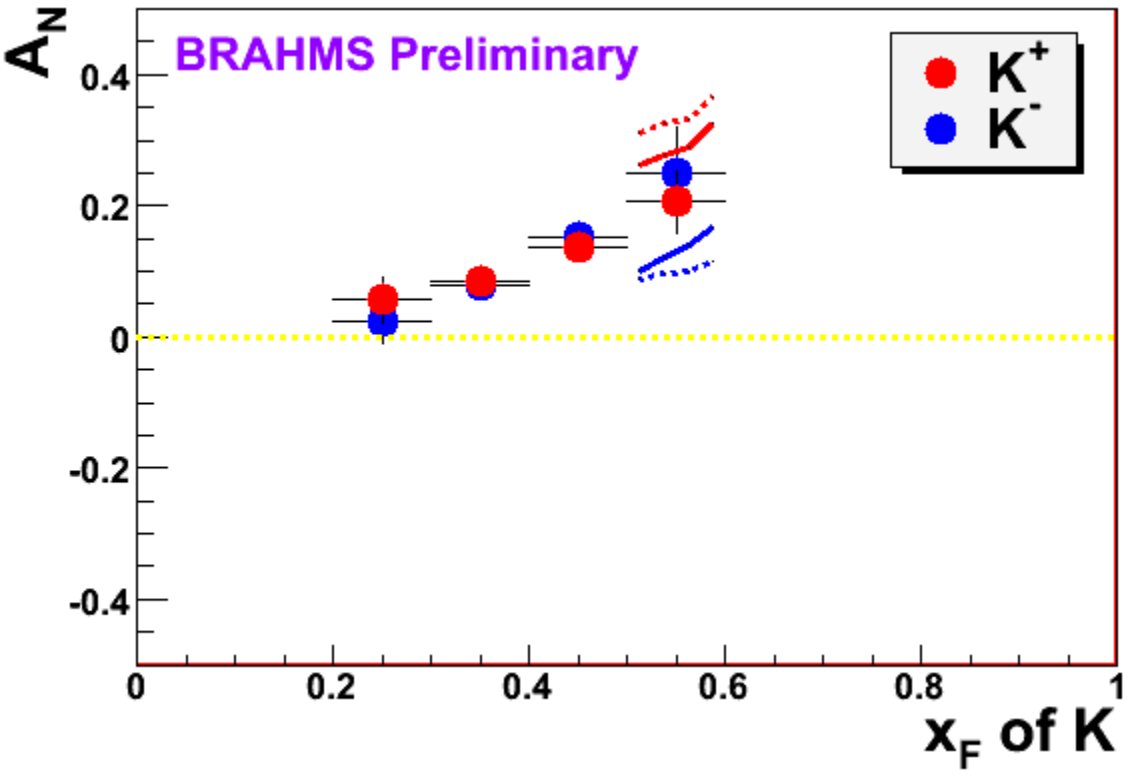




J.H. Lee, SPIN 2006


BRAHMS Preliminary
A_N
π^+
π^-
0.4
0.2
0
-0.2
-0.4
0
0.2
0.4
0.6

$$\sqrt{s} = 62GeV$$


BRAHMS Preliminary
A_N
K^+
K^-
0.4
0.2
0
-0.2
-0.4
0
0.2
0.4
0.6
0.8
1
x_F of K

We are also updating

- Gluon contribution
- Collins (twist-three) fragmentation contribution
- Stay tune,…

Kang,Qiu,Vogelsang,Yuan, to appear

NLO corrections to SSA

Vogelsang-Yuan, arXiv:0904.0410

- SSA in Drell-Yan as an example,

$$p_\uparrow(P_A, S_\perp)\, p(P_B) \to \gamma^*(Q^2, q_\perp) + X \to \ell^+\ell^- + X$$

$$\epsilon^{\alpha\beta} S_\perp^\alpha q_\perp^\beta = |S_\perp||q_\perp| \sin\phi$$

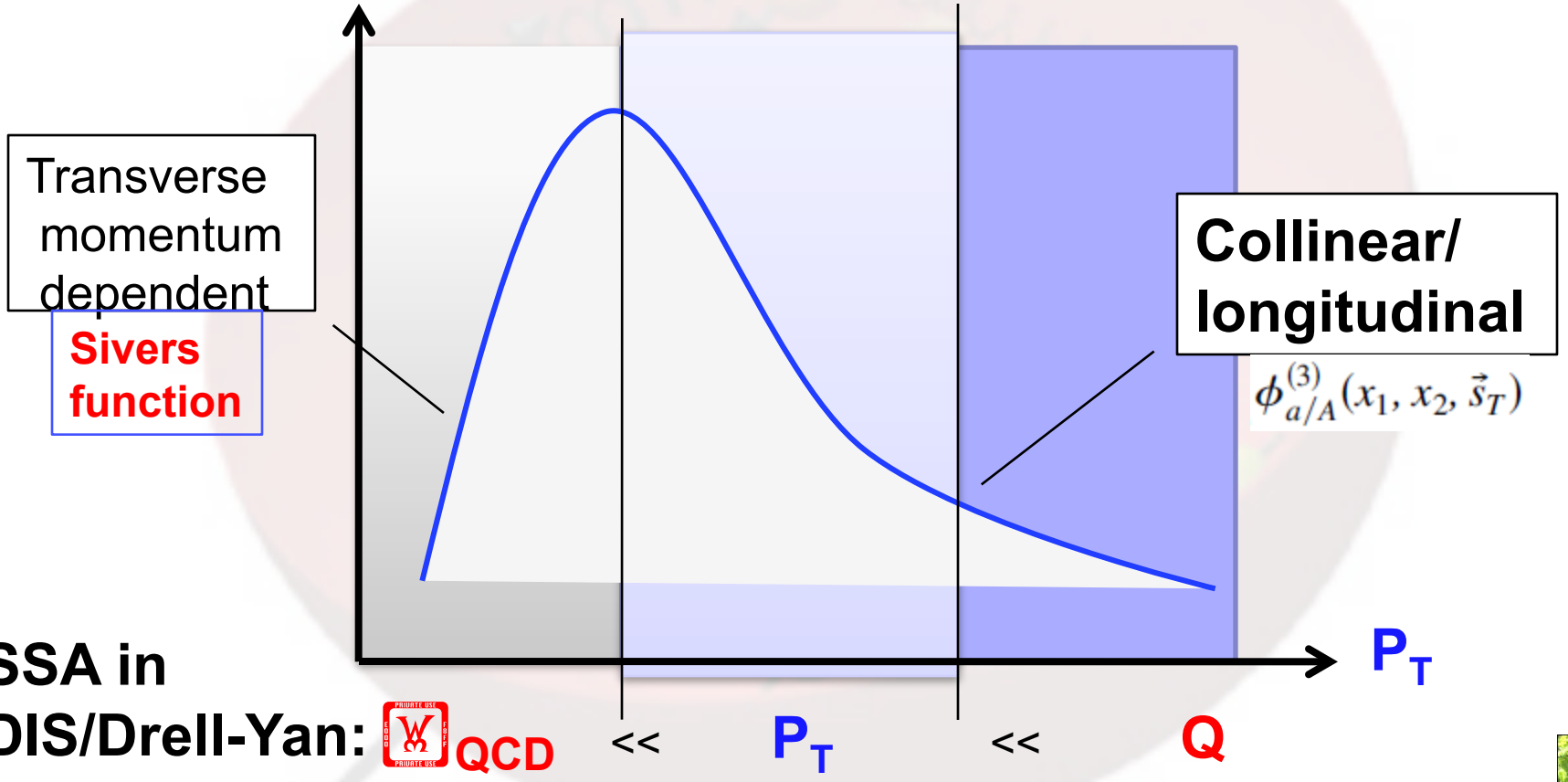
- **Collinear factorization**

$$\frac{d\langle q_\perp \Delta\sigma(S_\perp)\rangle}{dQ^2} = \sigma_0 \int \frac{dx_1}{x_1}\frac{dx_2}{x_2}\frac{dx'}{x'} T_{F,q}(x_1, x_2)\bar{q}(x')\mathcal{H}(x_1, x_2; x')$$

↓

Collinear functions, evolution: Kang-Qiu, 08;
Zhou-Yuan-Liang, 08
Braun et al., 0909.3410

A unified picture between TMD and twist-three (leading pt/Q)

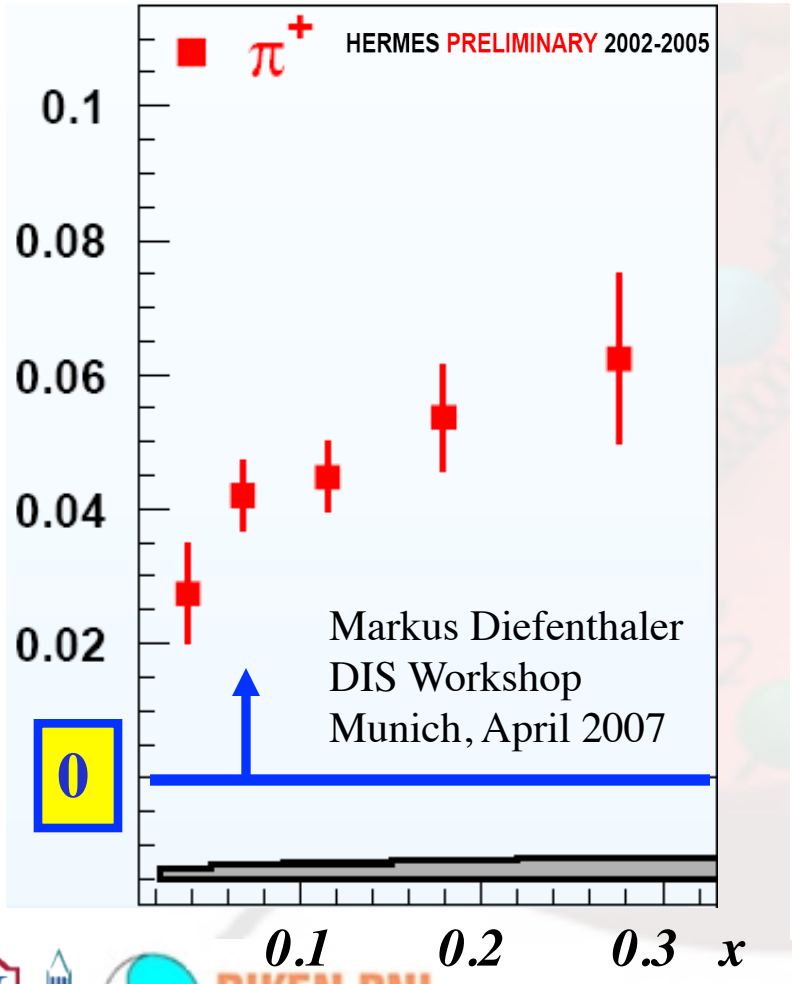


SSA in DIS/Drell-Yan:

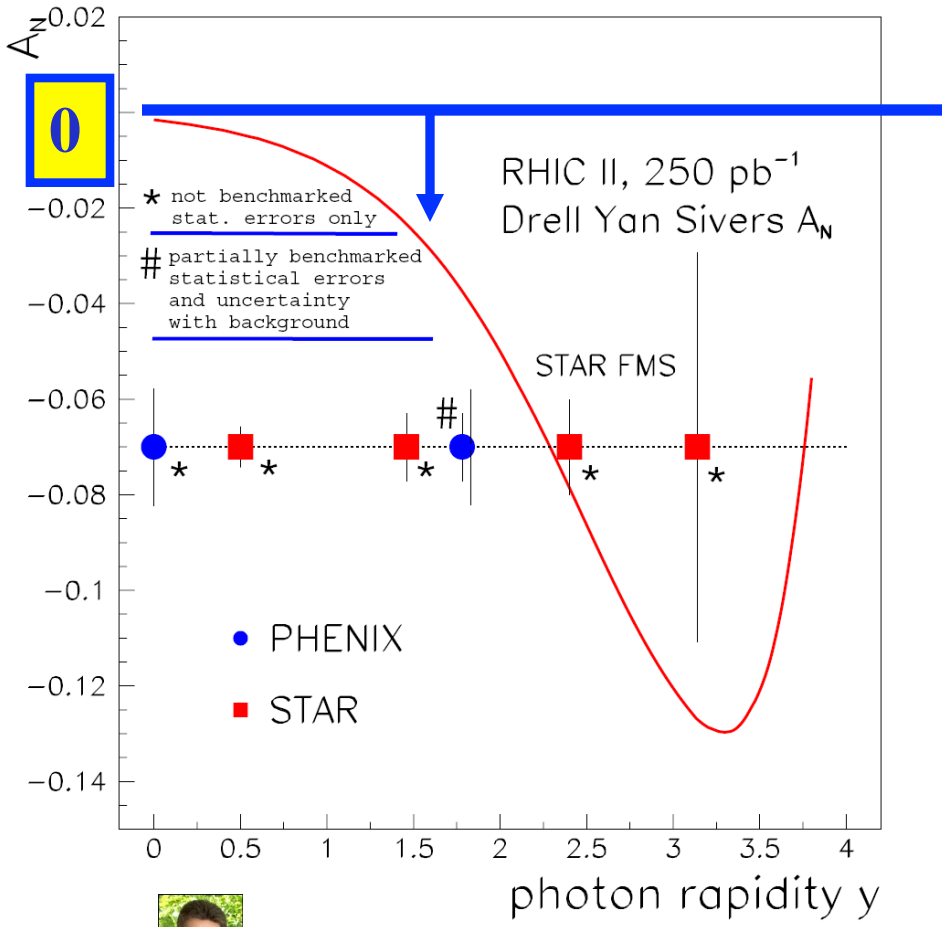
Ji-Qiu-Vogelsang-Yuan, 2006
Yuan-Zhou, 2009

Experiment SIDIS vs Drell Yan

HERMES Sivers Results



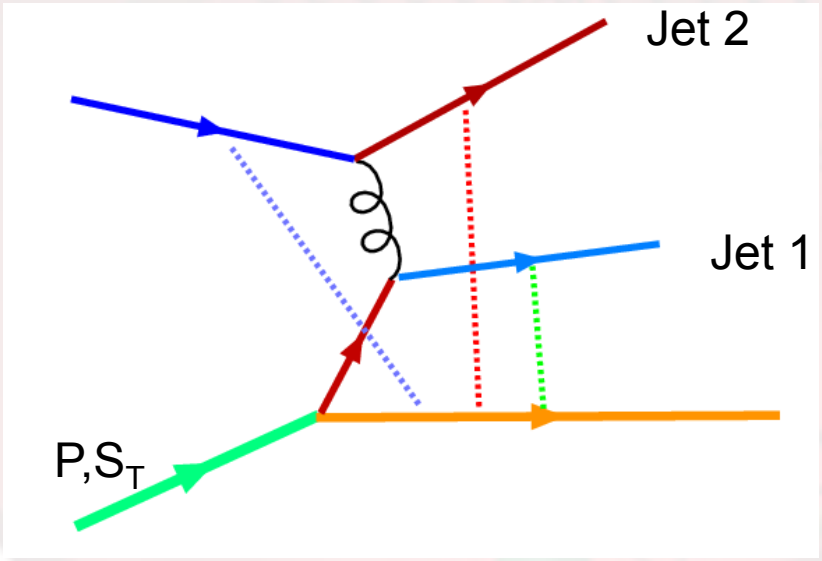
RHIC II Drell Yan Projections

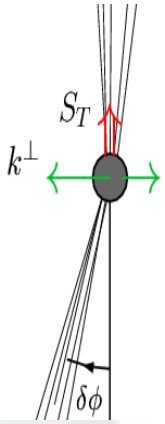


http://spin.riken.bnl.gov/rsc/
Les Bland, preliminary

Non-universality: Dijet-correlation at RHIC

- Initial state and/or final state interactions





Boer-Vogelsang 03

Standard Factorization breaks, no universality!

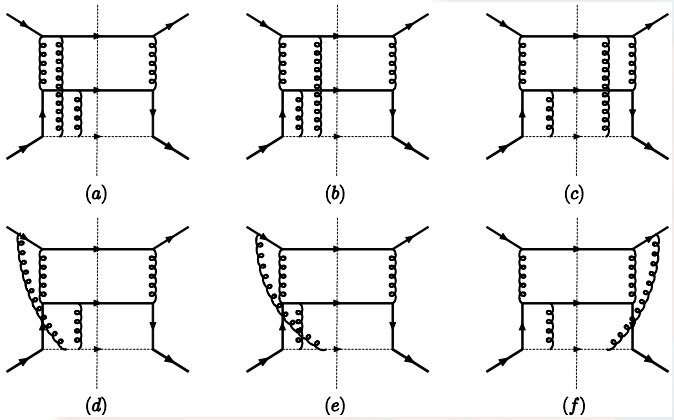
Bacchetta-Bomhof-Mulders-Pijlman-Rogers, 04-10
Qiu-Vogelsang-Yuan 07
Collins-Qiu 07
Vogelsang-Yuan 07

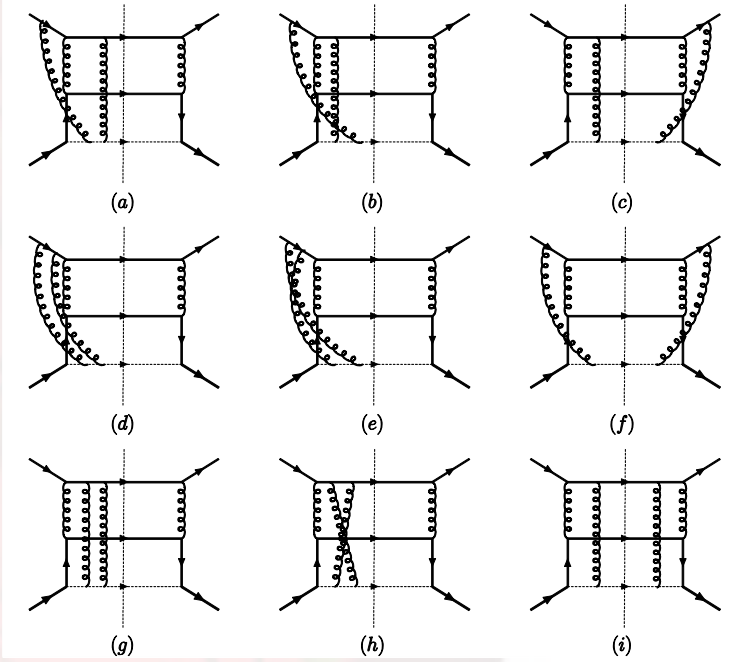
BERKELEY LAB

RIKEN BNL Research Center

The simple picture does not hold for two-gluon exchanges

Vogelang-Yuan, 0708.4398;
Collins, 0708.4410





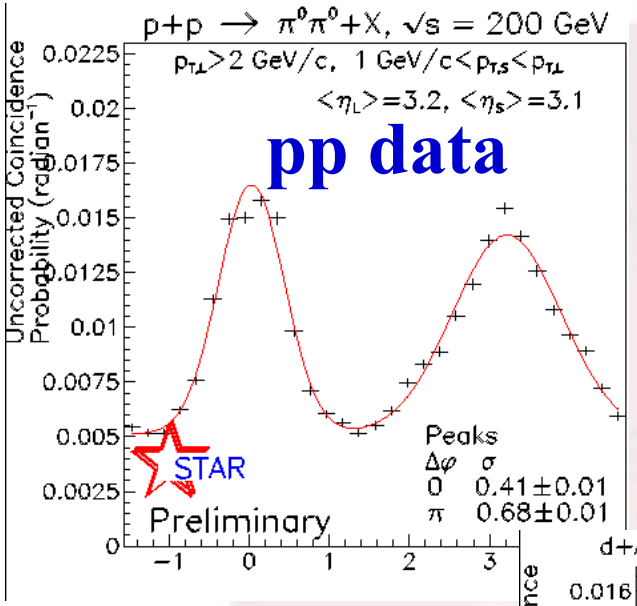
Becchetta-Bomhof-Mulders-Pijlman, 04-06

$$\mathcal{L}'_{v_a}(g_1,g_2;\xi) \equiv \mathcal{P}\exp\left(-ig_1\int_0^\infty d\lambda v_a\cdot A(\xi+\lambda v_a)\right)$$
$$\times\mathcal{P}\exp\left(-ig_2\int_0^\infty d\lambda v_a\cdot A(\xi+\lambda v_a)\right)$$
$$\times\mathcal{P}\exp\left(ig_2\int_0^{-\infty} d\lambda v_a\cdot A(\xi+\lambda v_a)\right)$$

$$\Rightarrow \mathcal{P}\exp\left(-ig_1\int_0^\infty d\lambda v_a\cdot A(\xi+\lambda v_a)\right)$$

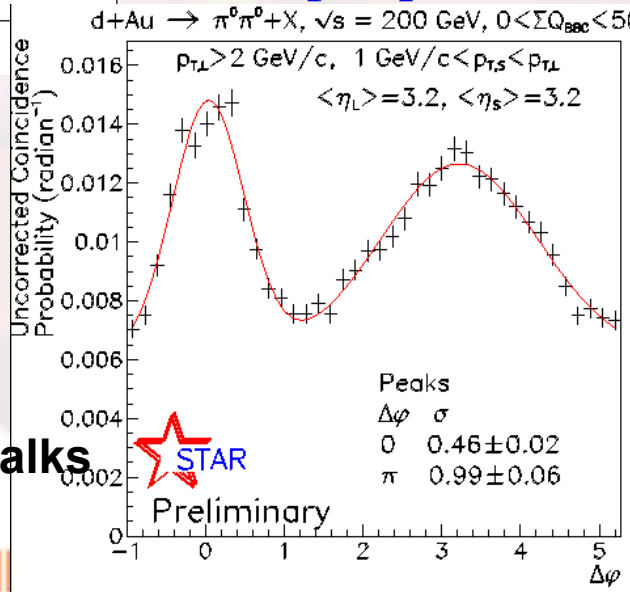
Integrated over transverse momentum

Dijet-correlation in pA collisions

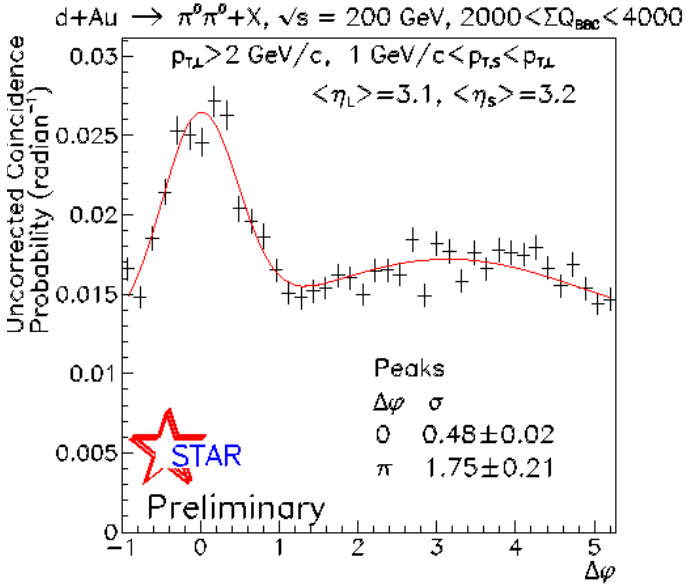


Qiu-Vitev 06
Marquet 07
Tuchin 09
Dumitru,Jalilian-Marian10
Marquet 10

dAu peripheral



dAu Central



Ogawa, APS 2010
Crawford and Citron's talks

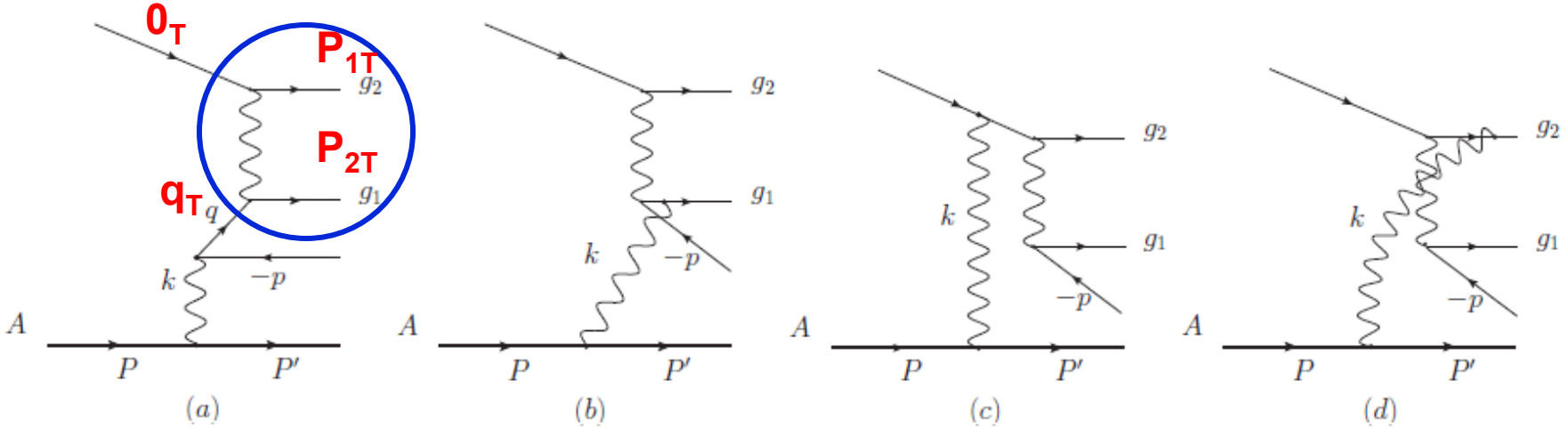
Universality of TMD at small-x?

- This has not been shown/studied in small-x physics
- Different assumption and summation are made
- We want to make a model calculations suitable for both TMD and small-x approximation
  - **Summation to all order is crucial**

Model calculations

- $qq' \to qq'$ channel

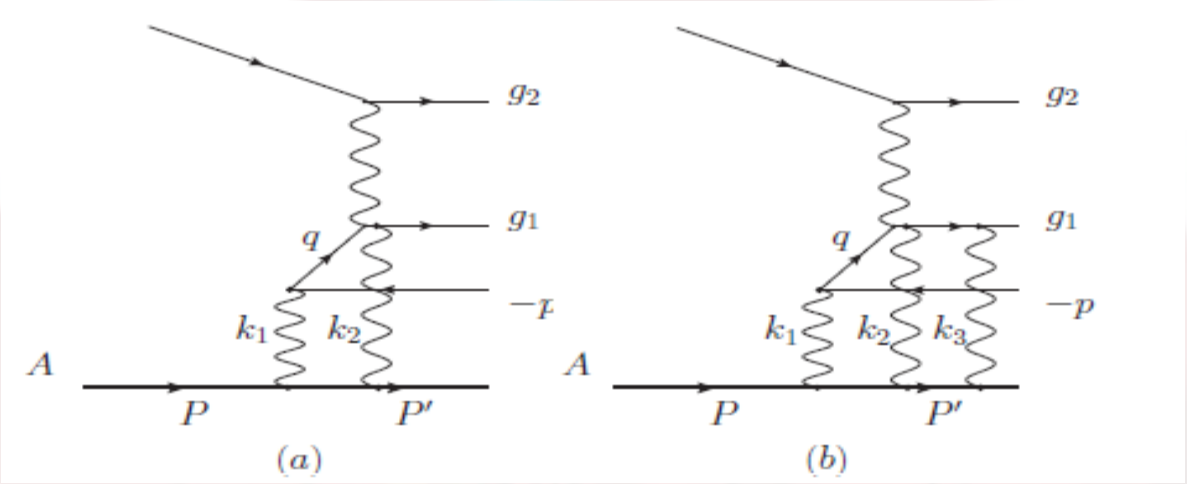
Xiao,Yuan, arXiv:1003.0482



- q_t dependence, $q_T = P_{1T} + P_{1T} \ll P_{1T} \sim P_{1T}$

$$\tilde{q}(x, q_\perp) = \frac{x}{32\pi^2} \int \frac{dp^-}{p^-} \frac{d^2k_\perp}{(2\pi)^4} (4P^+p^-)^2 \left| A^{(tot)}(k,p) \right|^2 \quad A^{(1)}(k,p) = g g_1 \frac{1}{k_\perp^2 + \lambda^2} \left[\frac{1}{D_1} - \frac{1}{D_2} \right]$$

Multi-gluon exchange



$$A^{(2)}(k,p) = \frac{i}{2}g^2 \int d[1]d[2] \left\{ g_1^2 \left[\frac{1}{D_1} + \frac{1}{D_2} - \frac{1}{D_{21}} - \frac{1}{D_{22}} \right] + g_1 g_2 \left[\frac{2}{D_2} - \frac{2}{D_{21}} \right] \right\}$$

$$A^{(3)}(k,p) = \frac{1}{3!}g^3 \int d[1]d[2]d[3] \left\{ g_1^3 \left[\frac{1}{D_2} - \frac{1}{D_1} + \frac{3}{D_{13}} - \frac{3}{D_{21}} \right] + g_1^2 g_2 \left[\frac{3}{D_2} + \frac{3}{D_{13}} - \frac{3}{D_{21}} - \frac{3}{D_{22}} \right] + g_1 g_2^2 \left[\frac{3}{D_2} - \frac{3}{D_{21}} \right] \right\}$$

All-orders

$$\tilde{q}\left(x,q_\perp\right)=\frac{xP^{+2}}{8\pi^4}\int dp^- p^- \int d^2R_\perp d^2R'_\perp d^2r_\perp e^{iq_\perp\cdot\left(R_\perp-R'_\perp\right)}e^{-igg_2\left(G(R_\perp)-G(R'_\perp)\right)}$$
$$V\left(r_\perp\right)V\left(r'_\perp\right)\left\{1-e^{igg_1\left[G\left(R_\perp+r_\perp\right)-G(R_\perp)\right]}\right\}\left\{1-e^{-igg_1\left[G\left(R'_\perp+r'_\perp\right)-G\left(R'_\perp\right)\right]}\right\},$$

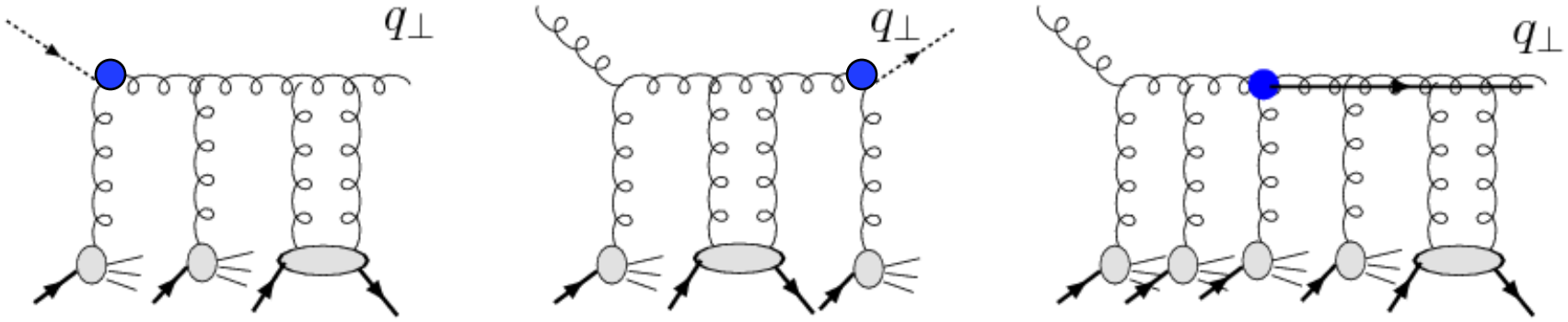
- DIS process (g_2-term disappear)

$$\tilde{q}\left(x,q_\perp\right)=\frac{xP^{+2}}{8\pi^4}\int dp^- p^- \int d^2R_\perp d^2R'_\perp d^2r_\perp e^{iq_\perp\cdot\left(R_\perp-R'_\perp\right)}V\left(r_\perp\right)V\left(r'_\perp\right)$$
$$\times\left\{1-e^{igg_1\left[G\left(R_\perp+r_\perp\right)-G(R_\perp)\right]}\right\}\left\{1-e^{-igg_1\left[G\left(R'_\perp+r'_\perp\right)-G\left(R'_\perp\right)\right]}\right\},$$

- They are not the same, **Non-universality**

Realistic QCD dipole model

- Following Kovchegov-Mueller 1998



DIS-type **Drell-Yan-type** **pA→Dijet-like**

$$\tilde{N}(\underline{x}) = \int d^2b \frac{N_c^2 - 1}{\pi^2 \alpha N_c \underline{x}^2} (1 - exp[-\frac{\sqrt{R^2 - b^2}}{2\lambda} \underline{x}^2 \tilde{v}(\underline{x})])$$

Time-reversal invariance

Certainly will be different

Marquet,Venugopalan,Xiao,Yuan, work in progress

Comments

- Light-cone gauge does not help
- Non-universal for the kt-dependent parton distribution at small-x, will affect the phenomenological interpretations
- Remain to be seen that how/does the classical field calculation contain these effects

Journey forward at RHIC

- SSA in forward direction impose theoretical challenge
  - Pt-dependence, Kang et al, work in progress
  - Eta/pi0 SSA
- Dijet-correlation not only probe small-x saturation, but also the QCD dynamics (initial/final state interaction effects)